

Craton formation in Late Archean subduction zones revealed by first Greenland eclogites

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ABSTRACT

It is now well established that the early continental crust was formed by melting of basaltic lithologies such as amphibolite and eclogite. However, considerable uncertainty surrounds the geologic environment in which melting took place. Commonly invoked options range between melting at the underside of oceanic plateaus above mantle plumes or melting of oceanic lithosphere during shallow subduction. Distinguishing between these scenarios has important implications for the early evolution of continents. We use the first eclogites discovered from the North Atlantic craton (NAC) to constrain the formation of the deep root to this continent. Late Archean eclogite xenoliths (2.7 ± 0.3 Ga) from a kimberlite in West Greenland are broadly coeval with a major regional episode of tonalite-trondhjemite-granodiorite (TTG) magmatism. Major and trace element systematics of the eclogites reveal a highly refractory character that is mirrored by NAC peridotites. Moreover, the refractory eclogites define a complementary relationship to the Late Archean TTG granitoids from the NAC, and their elevated garnet $\delta^{18}\text{O}$ values along with negative Eu anomalies suggest seafloor-altered oceanic crust as the most viable eclogite protolith. These results from Greenland provide strong support for a model in which early continental crust grew by melting of basaltic slabs in subduction zones, where tectonic stacking of down-going oceanic lithosphere provided the mechanism that coupled formation of cratonic crust and mantle.

INTRODUCTION

There exists a general consensus that the tectonomagmatic processes that led to the formation of Archean continents must have been different from modern continental growth given the significant compositional differences between ancient and Phanerozoic continental lithosphere domains (Griffin et al., 2009). Among the key differences are the typically much stronger depletion of Archean cratonic mantle and the occurrence of voluminous tonalite-trondhjemite-granodiorite (TTG) gneisses in Archean crustal terrains. The compositions of TTG gneisses have been explained by melting of basaltic lithologies in the form of either amphibolite or eclogite (Rapp and Watson, 1995; Foley et al., 2002). Controversy centers around whether melt extraction occurred at the underside of thick oceanic plateaus (Bedard, 2006) or in subduction zones (Rollinson, 2010), but, regardless, both mechanisms require elevated thermal gradients prevalent during the Archean in order to operate (Herzberg et al., 2010).

Here, we discuss geochemical, oxygen isotope, and Pb-Pb age data from the first discovered Greenland eclogites, which enables us to refine the mode of formation of the North Atlantic craton (NAC). These new constraints are of particular importance because Late Archean NAC assembly is widely considered a prime example of craton formation by subduction and collision processes (Griffin et al., 2004; Pearson and Wittig, 2008; Windley and Garde, 2009).

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FIRST MANTLE ECLOGITES FROM GREENLAND

The Nunatak-1390 Xenolith Occurrence

A suite of eclogite xenoliths was discovered in kimberlite boulders on Nunatak-1390, ~150 km southeast of Nuuk, West Greenland (Fig. 1A). The host angular kimberlite boulders have coherent-magmatic features and large diameters (up to 1 m) indicating derivation from a proximal dike system beneath the inland ice margin. At present, no age exists for

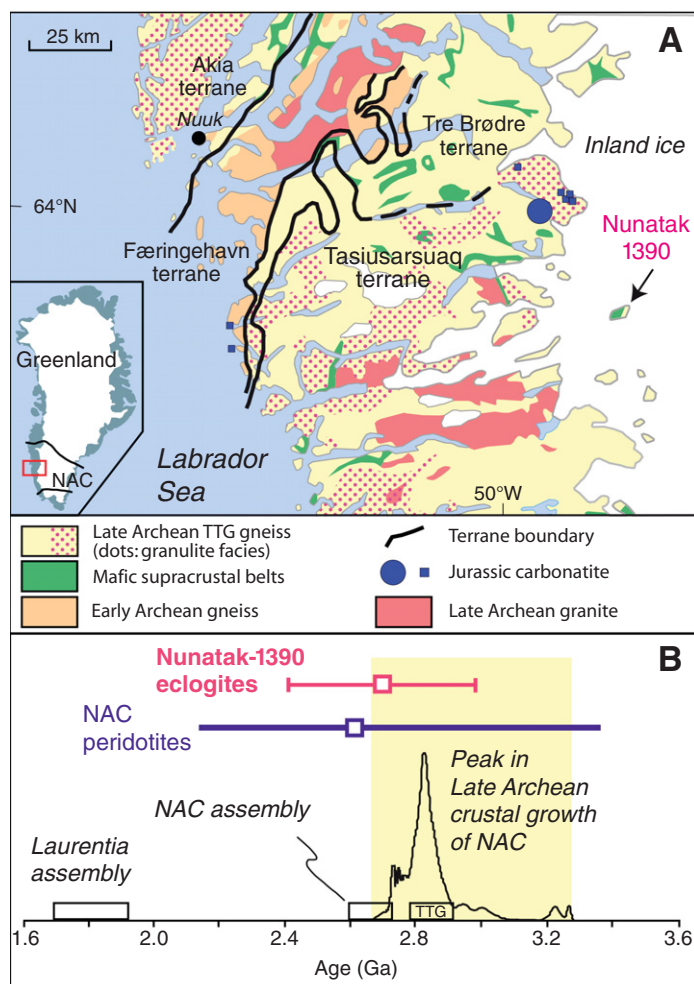


Figure 1. A: Geological map of the central North Atlantic craton (NAC) showing the Nunatak-1390 eclogite xenolith occurrence in the Tasiusarsuaq terrane. B: Age comparison between eclogites (this study), mantle peridotites (Wittig et al., 2010), and Late Archean tonalite-trondhjemite-granodiorites (TTGs) of the NAC. Relative probability curve utilizes the detrital zircon database of Nutman et al. (2004) and indicates a peak in Late Archean crustal growth in the central NAC. Rectangles indicate TTG magmatism and NAC accretion in the Tasiusarsuaq terrane (Naeraa and Schersten, 2008).

the Nunatak-1390 kimberlite, but its Sr-Nd-Pb isotope compositions overlap with those of Jurassic carbonatite intrusives ~30 km northwest (165–155 Ma; Tappe et al., 2009), indicating a genetic and temporal link. The bedrock of Nunatak-1390 consists of ca. 2.9–2.7 Ga TTG gneisses and mafic supracrustal units of the Late Archean Tasiusarsuaq terrane of the central NAC (Naeraa and Schersten, 2008).

We recovered 11 eclogite xenoliths (1 to 4 cm) consisting of roughly equal proportions of interlocking garnet and clinopyroxene (Fig. DR1 in the GSA Data Repository¹). Equilibration temperatures range from 780 to 990 °C (for details of methods, and supplemental data files, see the GSA Data Repository), corresponding to last equilibration depths of ~110–150 km when projected to the peridotite-derived NAC geotherm of Sand et al. (2009). Hence, our (*P*)-*T* estimates indicate that the Nunatak-1390 eclogite xenoliths were sampled from well within the NAC mantle lithosphere.

“PRISTINE” VERSUS “OVERPRINTED” REFRACTORY ECLOGITES

All Nunatak-1390 eclogites are characterized by relatively high-MgO garnet (14.7–19.9 wt%) plus low-to-moderate Na₂O (3.6–4.8 wt%) and Al₂O₃ (5.4–7.8 wt%) clinopyroxene indicative of previous loss of a melt component (cf. Ireland et al., 1994; Rollinson, 1997; Jacob and Foley, 1999). However, based on clinopyroxene and garnet trace element characteristics, we identified two types of refractory eclogite: an incompatible element-enriched “overprinted” group and a depleted “pristine” group (Fig. 2). Importantly, there is complete overlap in heavy rare earth element (HREE) patterns between pristine and overprinted subgroups, which, in concert with the similar major element compositions, testifies to a common origin. Of further note, only pristine eclogites record negative Eu anomalies (garnet Eu/Eu* = 0.42–0.83), whereas such subtleties in the mineral trace element patterns have been largely obliterated in the overprinted eclogites (see also Zr-Hf depletion in Fig. 2B).

Pristine and overprinted refractory eclogites show distinct Pb-Pb clinopyroxene isotope systematics (Fig. 2). The overprinted, light REE (LREE)-enriched clinopyroxenes (592572A, 592572D) do not define a meaningful isochron. However, intercepts on the Stacey and Kramers (1975) Pb isotope growth curve suggest Paleoproterozoic model ages of ca. 2.10 to 2.21 Ga, which most likely record the timing of metamorphic overprinting. Clinopyroxene from eclogite 592572F yielded Pb isotope compositions similar to the host kimberlite such that a significant portion of the Pb analyzed represents kimberlite infiltration. In contrast, multiple clinopyroxene grains from the pristine eclogite xenoliths 488585A (Fig. DR1) and 514320 define a statistically meaningful Pb-Pb secondary isochron age of 2.70 ± 0.29 Ga (2-sigma, MSWD = 0.43), interpreted as the timing of eclogite formation. This age most likely coincides with the loss of melt component(s). Importantly, the Pb isotope data defining the secondary isochron intersect the growth curve at ca. 2.62 Ga, and this Late Archean model age is in good agreement with the isochron age of 2.70 ± 0.29 Ga (Fig. 2C).

Despite the distinct clinopyroxene Pb isotope compositions, garnets from both the pristine and overprinted eclogites have identical $\delta^{18}\text{O}$ values that range between 5.9‰ and 6.4‰ (Fig. 3C). These $\delta^{18}\text{O}$ values are significantly higher than pristine mantle ($5.5\text{‰} \pm 0.4\text{‰}$) and most likely fingerprint low-*T* processes such as seawater alteration affecting a crustal protolith (Jacob, 2004). Although Williams et al. (2009) suggested that garnet $\delta^{18}\text{O}$ values can be altered from pristine mantle values during par-

¹GSA Data Repository item 2011332, analytical techniques and methods, Tables DR1–DR3, (analytical results), and Figures DR1–DR3 (photograph of eclogite xenolith 488585A and normalized trace element patterns of reconstructed bulk eclogites and eclogitic clinopyroxene and garnet), is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

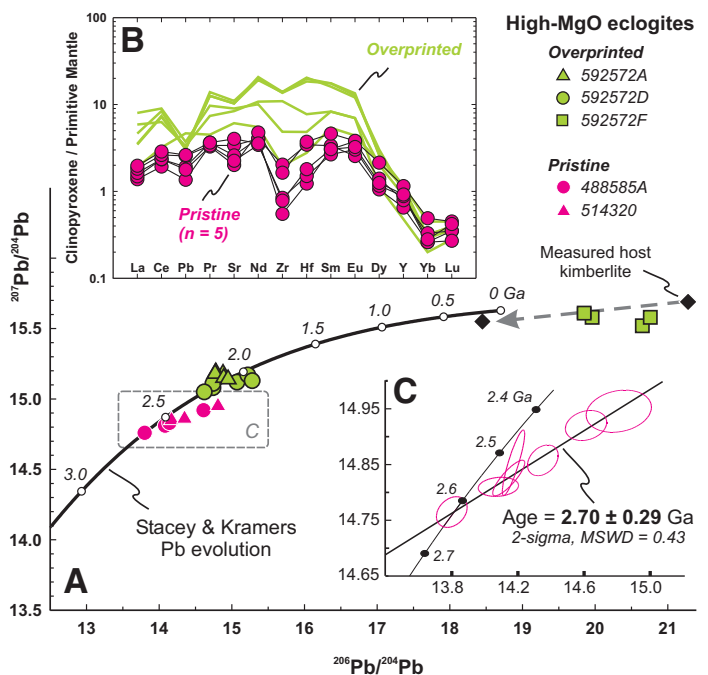


Figure 2. A: Measured clinopyroxene $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ for eclogites from Nunatak-1390. Stacey and Kramers (1975) Pb isotope growth curve shown for comparison. Arrow indicates age correction of the Nunatak kimberlite Pb isotope ratios to an emplacement age of 160 Ma. **B:** Normalized clinopyroxene trace element patterns of Nunatak eclogites. **C:** Clinopyroxene Pb-Pb secondary isochron.

tial melting of eclogite at mantle depths, only shifts toward low $\delta^{18}\text{O}$ were observed, in contrast to the “heavy” Nunatak eclogite signatures.

DISCUSSION

Coupling of Archean continental crust and its underlying cratonic mantle is well established (Pearson and Wittig, 2008), but uncertainty surrounds the roles that plume- and subduction-related processes may have played in early continent formation and growth (Bedard, 2006; Aulbach et al., 2007). Eclogites represent key archives of early continent evolution, because they can be directly linked to the genesis of the crust (Rapp and Watson, 1995; Rollinson, 1997; Barth et al., 2002a). However, there are only a few eclogite suites with both well-constrained ages and origins (e.g., Jacob and Foley, 1999; Barth et al., 2002b). While subduction (and by inference eclogite) plays a central role in Archean tectonic models of NAC evolution (Windley and Garde, 2009), until now there has been no mantle eclogite available to test these models.

CONSTRAINTS ON THE ECLOGITE PROTOLITH

The Nunatak eclogites exhibit prominent negative Eu anomalies (Fig. DR2) that point toward plagioclase fractionation in a “shallow” magmatic precursor that, in concert with crustal $\delta^{18}\text{O}$ signatures in garnet (Fig. 3C), suggests a basaltic oceanic crust protolith (e.g., Jacob, 2004). However, reconstructed whole-rock eclogite compositions show elevated MgO (13.3–14.5 wt%) and Cr₂O₃ (700–2400 ppm), and fairly low SiO₂ (47.4–48.4 wt%; Fig. 3A), indicative of a more refractory bulk composition than basalt. This apparent conflict is best explained by a model that requires loss of a melt component from a basaltic protolith, during subduction, to generate the refractory eclogite major element composition (e.g., Rollinson, 1997). Such a model is also consistent with the depleted highly incompatible (e.g., LREE and Sr) and enriched compatible (HREE and Y) trace element contents of the eclogites (Figs. 3B and DR2). Although

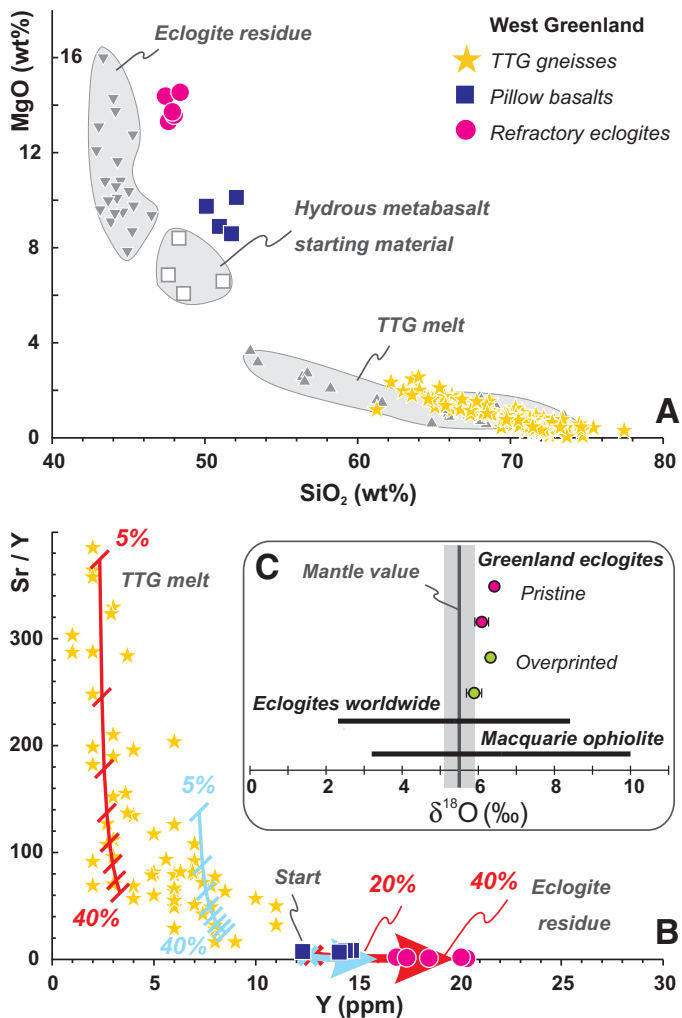


Figure 3. A: MgO versus SiO₂ of the refractory Nunatak eclogites and Late Archean tonalite-trondhjemite-granodiorites (TTGs) from West Greenland (Steenfelt et al., 2005) defining a complementary relationship. Eclogite symbol size accommodates a possible modal range between 40/60 and 60/40 garnet/clinopyroxene for calculated whole-rock compositions. Data for experimentally produced TTG melts (triangles-up) and corresponding eclogitic residues (triangles-down) are from Rapp and Watson (1995). Metabasalt starting materials (open squares) are contrasted with pillow basalts from the Late Archean Ivisartaq greenstone belt, central North Atlantic craton (Polat et al., 2008), which are starting compositions in the trace element modeling (Figs. 3B and DR2). B: Sr/Y versus Y of pristine Nunatak eclogites and Late Archean TTG gneisses from West Greenland. A batch melting model with Ivisartaq pillow basalt 485420 (Polat et al., 2008) as starting composition can explain the wide compositional range of the TTG gneisses by 5% to 40% partial melting (partition coefficients from Barth et al., 2002a: red curve/arrow at 1.8 GPa; and Klemme et al., 2002: blue curve/arrow at 3.0 GPa). With increasing degrees of melt extraction (red and blue arrows) the calculated eclogitic residue evolves by increasing Y, explaining the refractory Nunatak eclogites by at least 20% of TTG melt extraction from a basaltic protolith. C: Garnet δ¹⁸O values for Nunatak eclogites. Data for comparison from Jacob et al. (2004, and references therein).

rutile appears to be absent as indicated by the lack of negative Nb-Ta anomalies in bulk eclogite reconstructions (Fig. DR3), we cannot rule out its presence due to small sample size. Therefore, we focus on bulk REE distributions since they are largely independent of the presence/absence of rutile (Jacob and Foley, 1999).

ARCHEAN CRUST-MANTLE COUPLING

The Nunatak eclogites occur in the Tasiusarsuaq terrane, central NAC, an area dominated by Late Archean TTG gneisses (Fig. 1A). Our eclogite Pb-Pb secondary isochron of 2.70 ± 0.29 Ga (Fig. 2C) overlaps the main peak in crustal growth of the central NAC between 2.9 and 2.7 Ga (Nutman et al., 2004; Naeraa and Schersten, 2008). Furthermore, the eclogite age falls within the main mode of peridotite Re-Os model ages for NAC mantle lithosphere at 2.65 Ga (Wittig et al., 2010) (Fig. 1B). Despite the large uncertainties, these age constraints demonstrate coupling of the Late Archean TTG crust and underlying mantle lithosphere including the eclogitic component. Most importantly, the 2.7 Ga age of the Greenland eclogites supports the observation by Shirey and Richardson (2011) that mantle eclogite materials older than 3.0 Ga appear absent from the cratonic record. They suggest that the appearance of cratonic eclogites in most cratons after 3.0 Ga marks the onset of the Wilson Cycle of plate tectonics, when more frequent subduction and collision events became the most prominent continental growth mechanism.

The broad age overlap between NAC TTGs and Nunatak eclogites (Fig. 1B) suggests that the refractory eclogites represent residues of TTG melt extraction from an oceanic basaltic slab in an Archean subduction zone (cf. Barth et al., 2002b). This link is strengthened by the excellent compositional match between NAC TTGs plus eclogites with TTG-like melts and eclogitic residues produced from metabasalt dehydration melting experiments up to 3.2 GPa (Fig. 3A). In detail, the Nunatak eclogites have slightly higher SiO₂ than their experimentally produced analogues, indicative of involvement of a more SiO₂-rich basaltic protolith. Basaltic rocks that are compositionally similar to the least fractionated, seafloor-altered pillow basalts from the Late Archean Ivisartaq greenstone belt in the central NAC (Polat et al., 2008) appear to be the best candidate for the parent rock that may link eclogites and TTGs in West Greenland.

Trace element modeling further augments the proposed NAC eclogite-TTG link (Fig. 3B). The wide range in Sr/Y of Late Archean TTGs from West Greenland (and of TTGs in general) can be explained by 5% to 40% batch melting of typical Archean basalts. The low Sr/Y and high Y of the refractory Nunatak eclogites, however, require at least 20% tonalitic melt extraction. This is consistent with our REE modeling of the eclogitic residue (Fig. DR2), which indicates that the strong LREE depletion and fairly flat HREE patterns are produced by extensive melting (20% to 40%). Importantly, the calculated melt compositions yield steep REE patterns with pronounced LREE enrichment, strongly resembling typical Late Archean TTG gneiss from the central NAC (Steenfelt et al., 2005). The remarkably extensive melt extraction from the basaltic protolith in our model is consistent with melting experiments (Rapp and Watson, 1995; Foley et al., 2002) and explains the apparent lack of rutile in the eclogitic residues (cf. Klemme et al., 2002).

“SUBDUCTION-STACKING” DURING CRATON ASSEMBLY?

Although a number of recently proposed craton formation models have stressed an important role of plume magmatism (Bedard, 2006; Aulbach et al., 2007; Griffin et al., 2009), the age and compositional data for the refractory eclogite suite from West Greenland provide strong evidence for continental growth by stacking of oceanic lithosphere in Late Archean subduction zones (Helmstaedt and Schulze, 1989). Based on strong compositional layering and prominent repetitions in the mantle stratigraphy, Griffin et al. (2004) suggested that the cratonic mantle beneath West Greenland may represent the best example of a lithospheric root produced by tectonic stacking. Our (*P*-*T*) estimates for the Greenland eclogites clearly show that they were sampled from throughout the cratonic mantle section and are not restricted to its base, a major concern that was taken as evidence against the subduction-stacking hypothesis by Griffin and O'Reilly (2007) in other cratons worldwide.

The fact that mantle eclogites and peridotites from West Greenland are broadly coeval and record evidence of low-*P* origins suggests that they shared a common history as distinct parts of oceanic lithosphere. This heterogeneous oceanic lithosphere was most likely transferred to depth via shallow subduction preceding the collisions between Early Archean microcontinents (Windley and Garde, 2009). Petrological processing and tectonic stacking of this oceanic lithosphere during the Late Archean ultimately led to the growth of the NAC. Craton stabilization, however, required the newly formed continental lithosphere to cleanse itself of much of the dense eclogite component (Pearson and Wittig, 2008), leaving behind only minor refractory eclogitic pods nested within depleted peridotite. It is this poorly understood “cleansing” mechanism that seems to largely eradicate structural evidence of “subduction-stacking”, but as shown for West Greenland, the geochemical signatures of the rare eclogitic remnants reveal the early evolution of the craton.

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